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DEPARTMENT OF THE NAVY
NAVY EXPERIMENTAL DIVING UNIT
PANAMA CITY, FLORIDA 32407-5001

IN REPLY REFER TO:
NAVSEA Task 88-18A

NAVY EXPERIMENTAL DIVING UNIT

REPORT NO. 10-90

DIVER MONITORING SYSTEMS, ON-LINE AND PORTABLE FOR THERMAL AND METABOLIC MEASUREMENTS

JAMES R. BRAUN
LCDR JOHN A. STERBA, MC, USNR

MAY 1990

Submitted:

J.R. BRAUN
GS-12
Electrical Engineer

J.A. STERBA
LCDR, MC, USNR
Research Medical Officer

Reviewed:

J.W. McCARTHY
GM-14
Hyperbaric Engineer

H.J.C. SCHWARTZ
CAPT, MC, USN
Senior Medical Officer

B.K. MILLER, JR.
LCDR, USN
Senior Projects Officer

J.B. McDONELL
LCDR, USN
Executive Officer

Approved:

JAMES E.HALWACHS
CDR, U.S. Navy
Commanding Officer

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Physiological evaluation of diver performance required designing a portable diver monitoring system (P-DMS) for field use and an on-line diver monitoring system (O-DMS) for laboratory studies. For P-DMS and O-DMS, measurement requirements were similar: digit temperature (fingers/toes), body core temperature (esophageal/rectal), heart rate, and oxygen bottle pressure to determine oxygen consumption (VO2) using closed circuit underwater breathing apparatuses. Components of the P-DMS, reviewed in detail, include: solid-state data logger (Grant Instruments), waterproof bag with low-profile connector, special design minaturized digit thermistors (Yellow Springs Instruments). Data can be stored, on multiple runs, up to 12 hours. Results from field testing in the Arctic and laboratory are discussed. The O-DMS provides real-time monitoring and computer aquisition of data from two divers for: digit/core temperatures, 12-site skin temperature and heat flux, and oxygen bottle pressure for VO2. Accuracy: rectal/esophageal temperatures = ± 0.06°C, finger/toe temperatures = ± 0.10°C. Both P-DMS and O-DMS provides accurate and

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I. INTRODUCTION

In support of NAVSEA Task #89-18A, the Navy Experimental Diving Unit (NEDU) investigated portable recording devices and a commercially available computer based data acquisition and measurement systems. This provided the opportunity to develop a portable physiological monitoring device for a free-swimming diver and the on-line monitoring of two divers in a cold water swimming flume. Although two different problems, the measurement requirements were similar, i.e., temperature for fingers, toes, and body core, along with the electrocardiogram (ECG) for heart rate and oxygen bottle pressure for determination of oxygen consumption.

II. METHODS

A. PORTABLE DIVER MONITORING SYSTEM (P-DMS)

A market survey provided very little information on commercially available monitoring systems that satisfied our requirements for a compact, user-friendly data acquisition system that featured high accuracy, low cost, and a menu driven system. Two systems were used or under development by various laboratories of the Navy and Air Force. Systems identified were the Solid State Physiological In-Flight Data Recorder (SSPIDR) under development for the Naval Air Test Center by Systems Research Laboratories, (Dayton Ohio) and the Squirrel Meter/Logger manufactured by Grant Instruments (Cambridge, England) and distributed in the United States by Science/Electronics (Miamisburg, OH). Further investigation eliminated the SSPIDR because it was still under development and we were unable to purchase one.

This caused us to select the Squirrel as the portable diver monitoring system (P-DMS).

B. ON-LINE DIVER MONITORING SYSTEM (O-DMS)

To support the cold water studies of free-swimming divers in the NEDU cold water flume, a system was designed and built to measure and record physiological data simultaneously from two swimming divers. The following data was recorded for each diver in Table 1 with the number of channels in parenthesis.

Table 1

O-DMS PHYSIOLOGICAL DATA
(number of channels)

Heat flux sites (12)
Skin temperatures for fingers and toes (3 each hand, 2 each foot = 10).
ECG electrocardiogram (ECG), Lead I, II, III (1).
Esophogeal core temperature (1).
Rectal core temperature (1).
Hot water temperature for diver's tube suit inlet temperature (1).
Hot water temperature for diver's tube suit outlet temperature (1).
Tube suit water flow (1).
Oxygen bottle pressure (1).

Data collection was automated using a computer for acquisition, display and analysis.

III. RESULTS

A. PORTABLE DIVER MONITORING SYSTEM (P-DMS).

The Squirrel Meter/Logger was specially configured for NEDU by the Grant Instruments to be as compact as possible for diver comfort while still maintaining data collection and storage capability and without sacrificing reliability. The overall measurement of the P-DMS is 180 mm x 125 mm x 40 mm and weight, 1.0 kg (2.2 lb). The P-DMS unit has channels 1 to 8 for finger/toe temperatures, (range 0 to 75°C). Channels 9 and 10 are designed for rectal and esophageal body core temperature measurements (range 30-45°C). The P-DMS can also be modified by Grant Instruments to measure heat flux which would eliminate skin temperature channels. The analogue input channel (#11), measures from 0 to 20 milliamperes. It can be used to measure water pressure as a depth gauge or oxygen bottle pressure on a closed circuit underwater breathing apparatus (e.g. MK-15, MK-16, EX-19) to measure oxygen consumption. Channel 12, heart rate, has a range of 0 to 250 beats/minute.

Thermistor sensors, which serve as temperature inputs for the P-DMS are required to be the Yellow Springs Instrument (YSI) (Yellow Springs, OH) Model 400 series which measure 2,250 ohms at 25°C. The YSI Model 44033 was selected for finger and toe temperature monitoring because the temperature characteristics were identical to the YSI Model 400 series thermistor. YSI specially modified the 44033 for NEDU by reducing the thermistor size. The modified thermistor 44033 can be easily taped under the end of the finger or toe nail, without being noticed by the diver. To prevent thermistor wires from breaking with rigorous underwater work or free-swimming, extra electrical insulation was added by YSI to the modified 44033 thermistor. The rectal thermistor was the YSI, model 401. The esophageal thermistor was manufactured by Mallinckrodt Critical Care, Glenn Falls, NY (model 90050, size: 9 Fr.).

The data analysis program by Grant Instruments was purchased from Science/Electronics for IBM compatible personal computers (P.C.). The Zenith P.C., Model Z184, with a 3.5 in floppy disk drive and a 20 megabyte hard drive was purchased for interface with the P-DMS. The Zenith P.C. has a 2.5 hour rechargeable battery with a small portable printer (Brother, Zenith Data Systems, model M-1109, Vienna, VA) for data acquisition and analysis in the field. This system was successfully field tested during a two-week Arctic diving operation in 1989.

The data analysis program is menu driven, which makes it very easy to use. The recorded physiological data is easily transferred into the computer with the aid of a Science/Electronics supplied interface cable. In addition to the physiological data, time and the day and month is also transferred to the computer and appears on the data print out. The P-DMS has a capacity of 12 hours of recording with a new start/stop feature for multiple dives. This was an option requested by NEDU to allow multiple dives which can later be averaged and the data statistically analyzed.

Waterproofing was investigated to provide protection for the P-DMS when worn by a diver underwater. Although the recorder was worn under the diver's dry suit, there is always the possibility of dry suit flooding. The waterproof bag selected was a flexible plastic electronics bag manufactured by Goedecke & Co. (GmbH, Munchen 83, West Germany) and distributed in the United States by Pioneer & Co. (Westmont, N.J., model EWA, DU 3). The EWA bag measures 22 cm by 29 cm (9 in by 12 in) and is just large enough to hold the P-DMS. An electrical connector (Bendix, model JT07P-16-26S, Sidney, NY) provides a waterproof electrical interface between the P-DMS, through the water proof EWA plastic bag, and to the wiring harness. The harness was designed at NEDU for finger and toe thermistors, 3-lead ECG, oxygen bottle pressure transducer, and rectal and esophageal body core thermistor probes. The water proofing and connector system was successfully tested underwater to prevent leaking to a depth of 50 m (165 ft).

In Figure 1, a block diagram illustrates the intergral parts of the P-DMS. Figure 2 shows the wiring diagram of the P-DMS from the Grant series 1200 squirrel meter/logger, connector and the EWA waterproof bag to the diver's harness having the skin thermistors, core temperature probes, pressure channel and ECG leads. Excluded is the cable carrying data from the meter/logger to the computer. Figure 3 is actual data of a working dive in the Arctic (-2°C water) illustrating the graphical display of rectal core temperature (T_c), heart rate (HR), plus thumb and index fingertip temperatures (T_t, T_i) during rest and with exercise, free-swimming under the ice.

B. ON-LINE DIVER MONITORING SYSTEM (O-DMS).

The (O-DMS) system is built around a Zenith Z248 computer (IBM compatible) and has a 40 megabyte hard disc drive. Commercially available software was selected (Labtech Notebook, DAS, MetraByte, Tauton, MA.) due to being an easy to use menu driven system for data acquisition. This system has a maximum monitoring capacity of 1000 channels with on-line display up to 50 signals with 15 separate window displays on the monitor. Input signals can be plotted against time, or other variables. Data can be displayed as line or bar graphs, or digitally displayed as a meter.

Temperature data input is accomplished by using a DAS 16 analog to digital (A/D) converter (MetraByte Corp). The DAS 16 board is a full length board installed in the expansion slot inside the computer improving the computers speed and precision as a data acquisition system.

Thermistor data is inputted to the A/D converter via cascading EXP-RES resistance measurement accessory boards (MetraByte Corp.) cascaded to provide sufficient number of channels for two divers. Heat flux measurements are inputted to the A/D Converter by way of EXP-16 expansion sub-multiplexers (MetraByte Corp). These were also cascaded to provide the necessary number of channels.

Diving suit penetrators, umbilical cables, heat flux discs were provided by Hamburg Associates, Inc. (Jupiter, FL). The heat flux discs are a product of Concept Engineering, Old Saybrook, CT (part no. FR-050-TH44018).

In Figure 4, the block diagram is shown for the on-line diver monitoring system (O-DMS) from the monitoring harnesses for both diver 1 and 2 to the

computer and printer. Figure 5 illustrates the electrical connector that penetrates the diving suit with Figure 6 being the wiring diagram for this connection. Figure 7 shows the monitor's display of temperatures, heat flux (or flow), water flow and temperatures for the diver's tube suit, esophageal or rectal core temperatures and oxygen bottle pressure for both divers 1 and 2. Graphs (not shown) display mean foot, hand and body core temperatures for both divers allowing trends to be followed to anticipate reaching various termination criteria during experimental dives.

C. DEGREE OF ACCURACY

The portable diver monitoring system (P-DMS) and on-line diver monitoring system (O-DMS) used tested temperature probes that were calibrated using a large stirred water bath and two calibrated thermometers, traceable to the National Bureau of Standards in the temperature range of interest: (e.g. 35 to 37°C for esopageal and rectal core temperatures and 4 to 27°C for finger and toe temperatures. The P-DMS and O-DMS had an accuracy of $\pm$ 0.1°C for finger/toe temperature and $\pm$ 0.06°C for esophageal and rectal. On five working dives, divers had both P-DMS and O-DMS for side-by-side comparison of data over a two to three hour period. The P-DMS data was consistently within the accuracies of $\pm$ 0.1°C for fingers and toes, and $\pm$ 0.06°C for esophageal and rectal core temperatures. There is a correction factor feature of the O-DMS that also allows using any probe that may not be within the selection limit of $\pm$ 0.1°C of the calibration temperature.

IV. DISCUSSION

The portable diver monitoring system (P-DMS) was successfully used on four dives in the Arctic. The P-DMS was easy to use and did not cause any distraction during dives involving complex underwater tasks such as operating scientific equipment requiring hand and finger dexterity. In Figure 3, there was a preceeding 30-min period of rest which demonstrated immediate cooling of the index finger due to restriction of blood flow from a tight inner glove. Even with the subsequent 30-min period of underwater swimming, the index finger temperature never rose higher than 8°C, which was within the fingertip temperature painful range of 8 - 10°C (1). After 20 unmanned experiments at NEDU with the P-DMS using a well-stirred bath, four man-dives in the Arctic, and five additional man-dives in the NEDU cold water flume with data compared to the simulataneously used on-line diver monitoring system (O-DMS), accuracy, reproducibility, and reliability of the P-DMS was determined to be acceptable for use in physiology research.

The O-DMS proved to be very reliable and accuracy was maintained throughout rigorous use during two protocols involving dry suit dives in 2°C water, with simulated work in a submersible and free-swimming (1-3). These Protocols included the induction of clinical hypothermia with immersion in an ice bath followed by rewarming in an isolated cold air room (4-6), and underwater fin swimming in the NEDU Cold Water Flume (7-9).

For both P-DMS and O-DMS, finger and toe thermistors are taped in place with only a small piece of tape on the nail and digit pad to prevent any circumferential restriction of digit blood flow. The rectal thermistor was inserted 15 cm and taped in place in the gluteal fold. The esophageal thermistor was swallowed through the nose, held in place at 43 cm from the

nostrils also by tape. The three-lead electrocardiogram is modified to reduce chest muscle artifact by placing leads on the superior and inferior aspects of the sternum, with one lead at the standard left mid-axillary line position. This lead configuration gives a close approximation of Lead II, with adequate P waves and QRS complexes for rate and dysrhythmia monitoring.

V. CONCLUSION

The portable and on-line diver monitoring systems (P-DMS, O-DMS) were designed to provide collection of accurate and reproducible physiological data in the field and laboratory, respectively. Sufficient use of these systems has determined that both the P-DMS and O-DMS are reliable to be used in diving physiology research.

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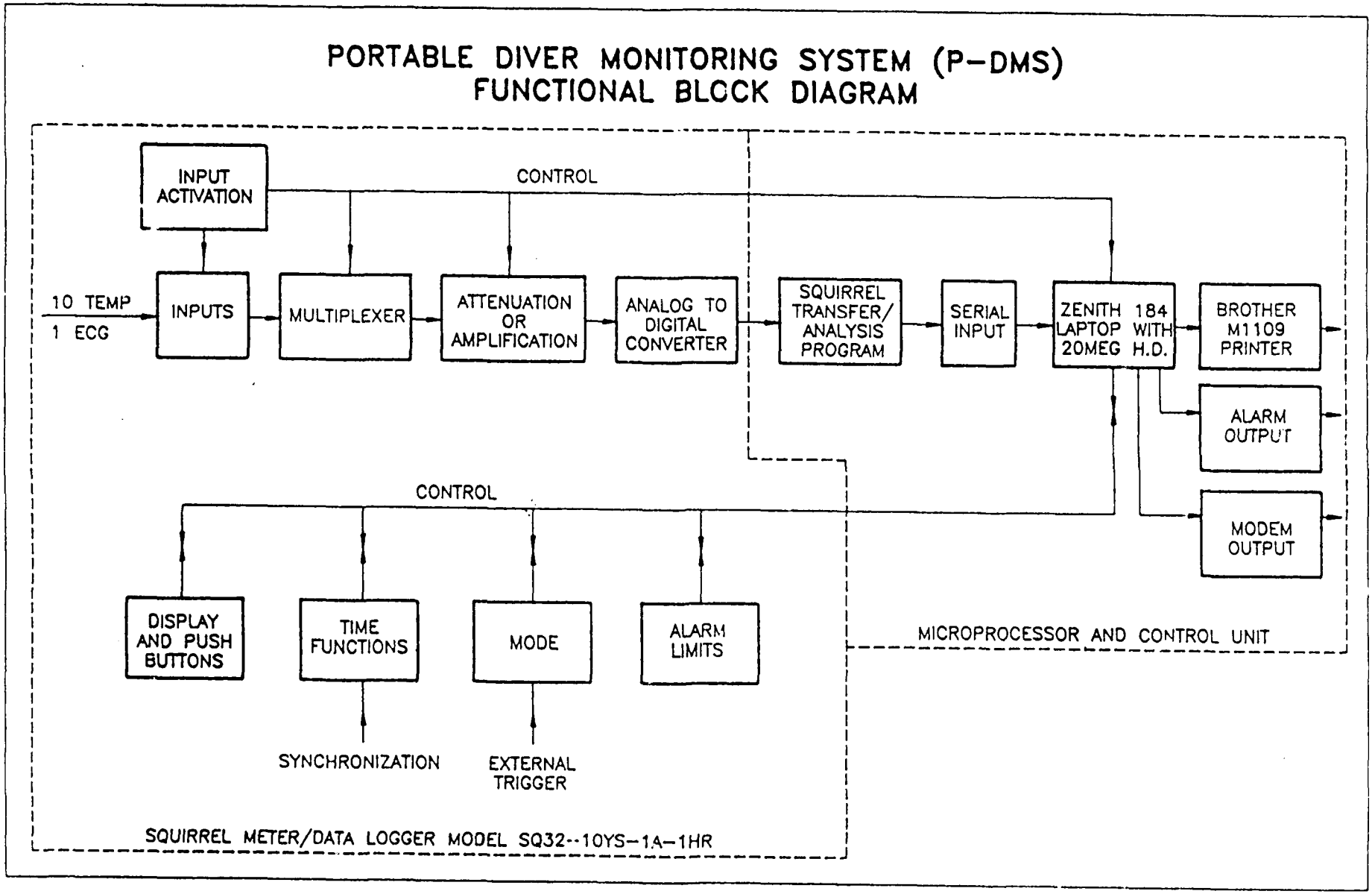


FIGURE 1 PAGE 11

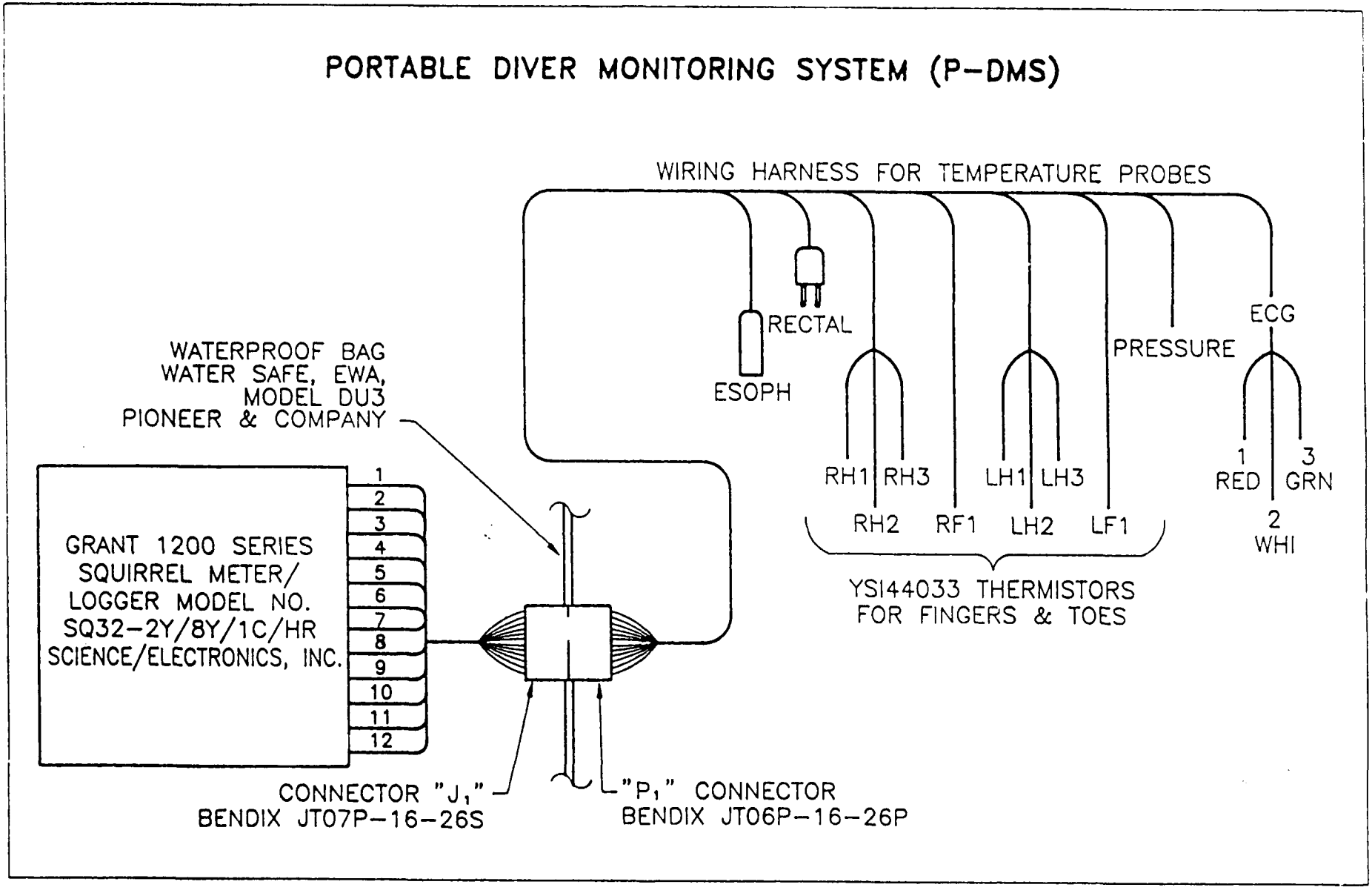


FIGURE 2 PAGE 12

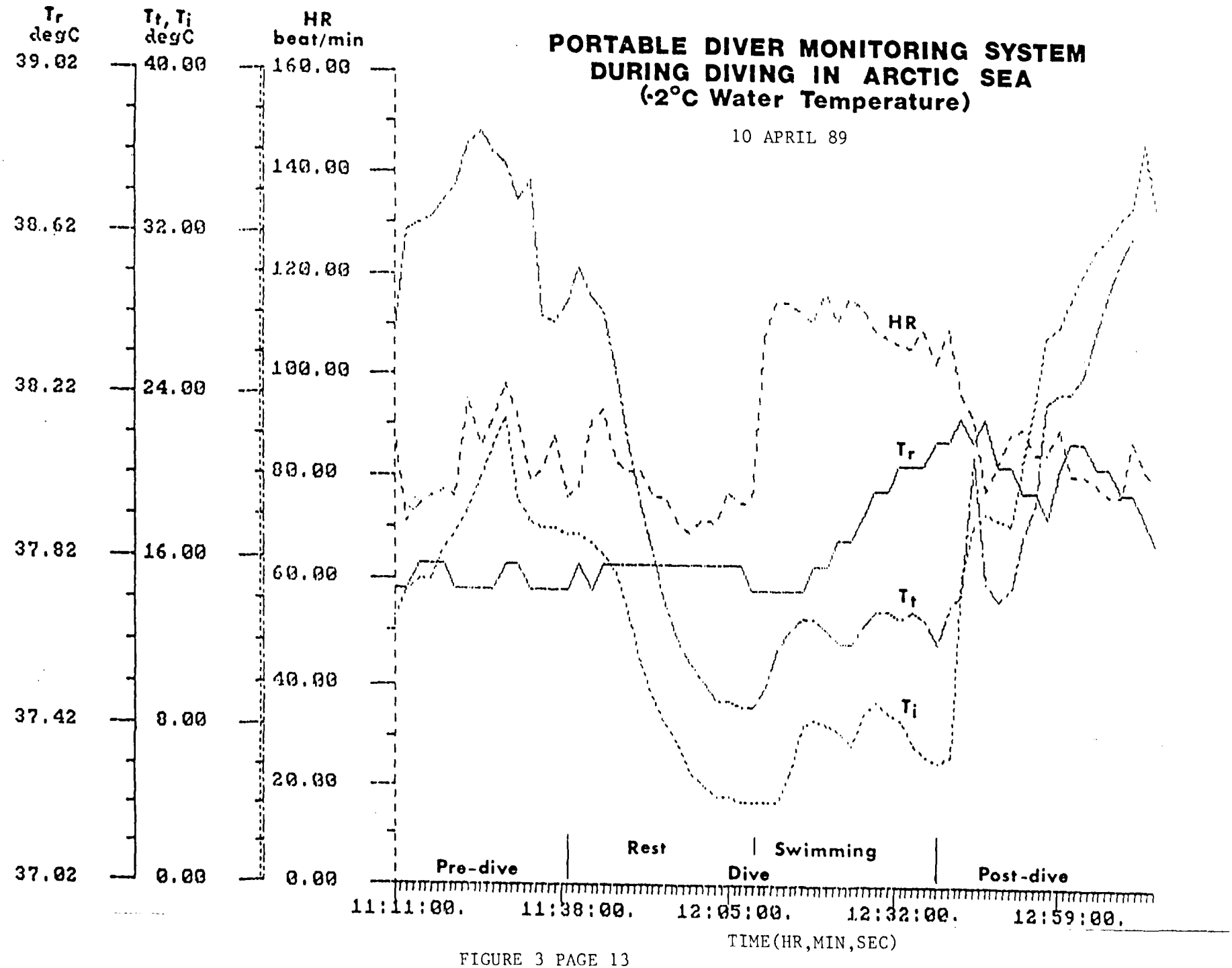


FIGURE 3 PAGE 13

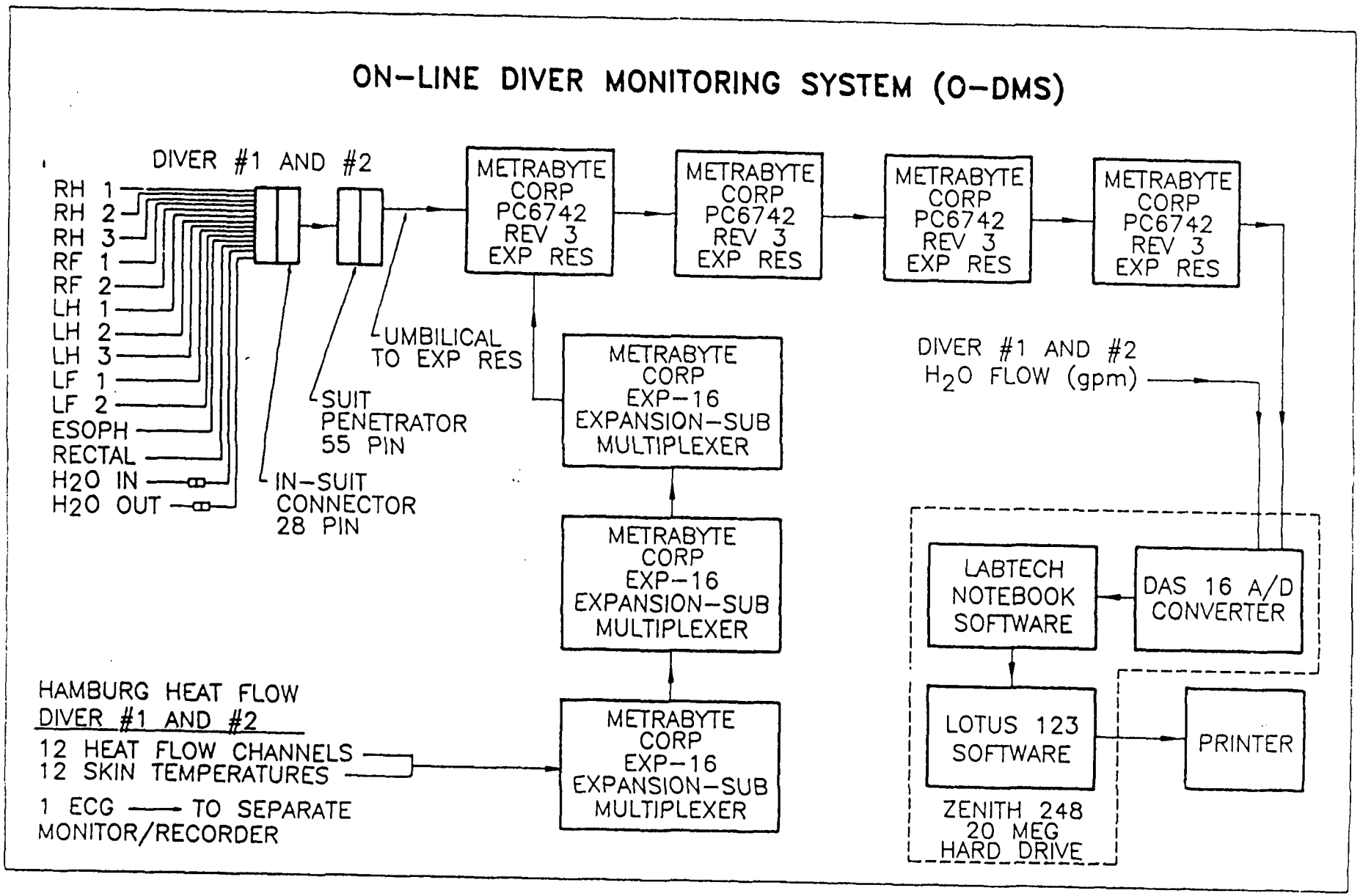
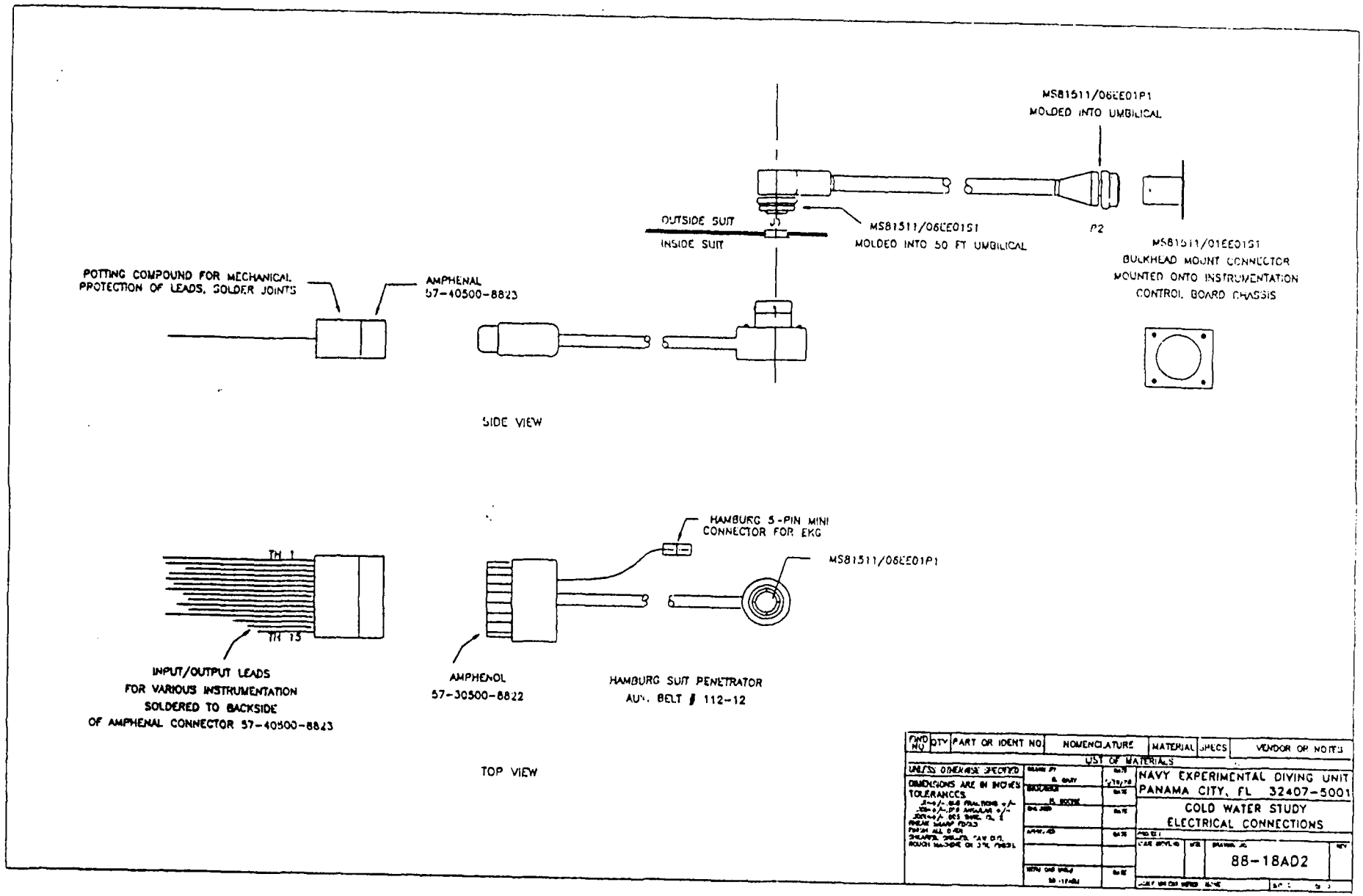


FIGURE 4 PAGE 14



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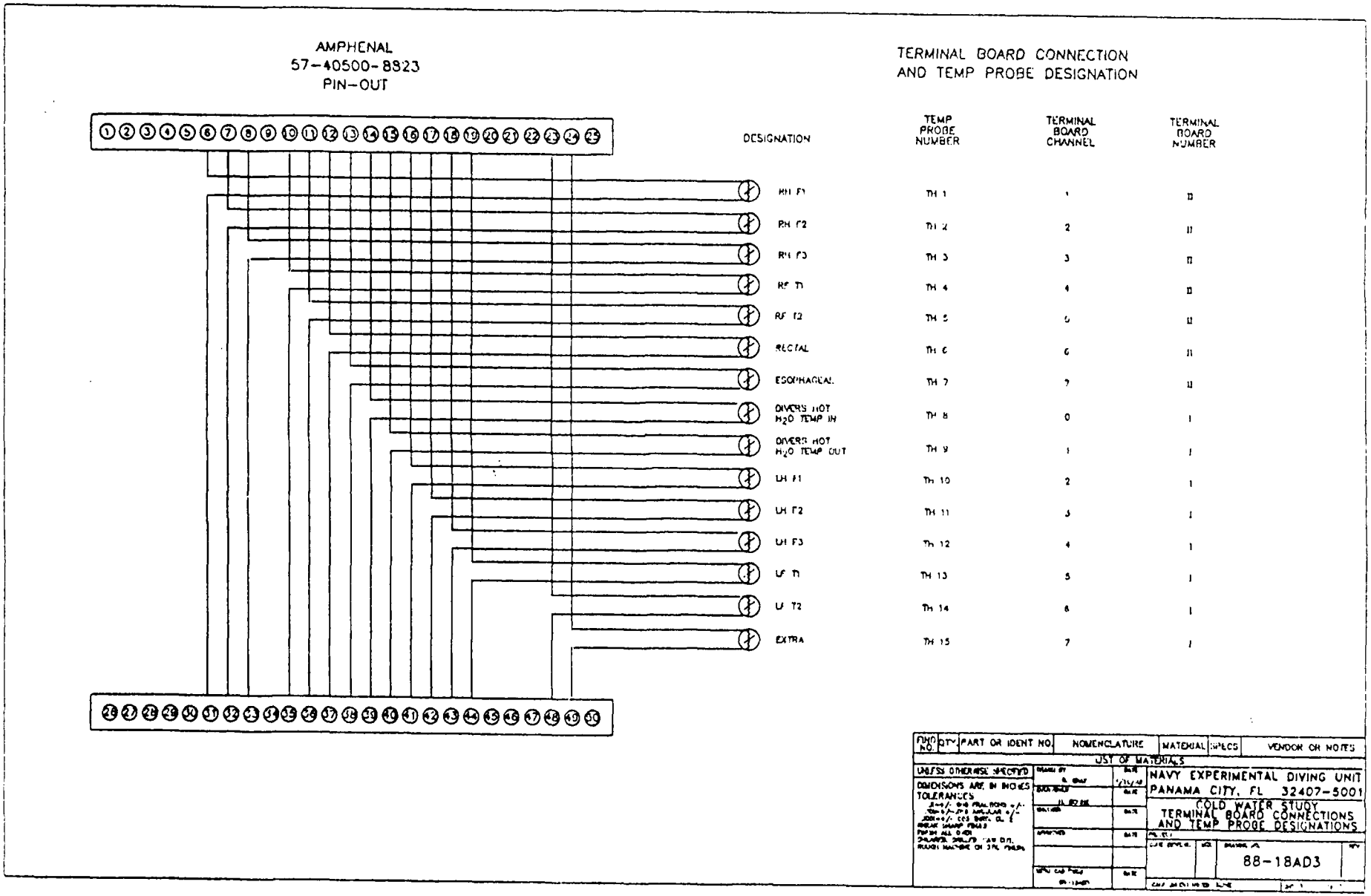
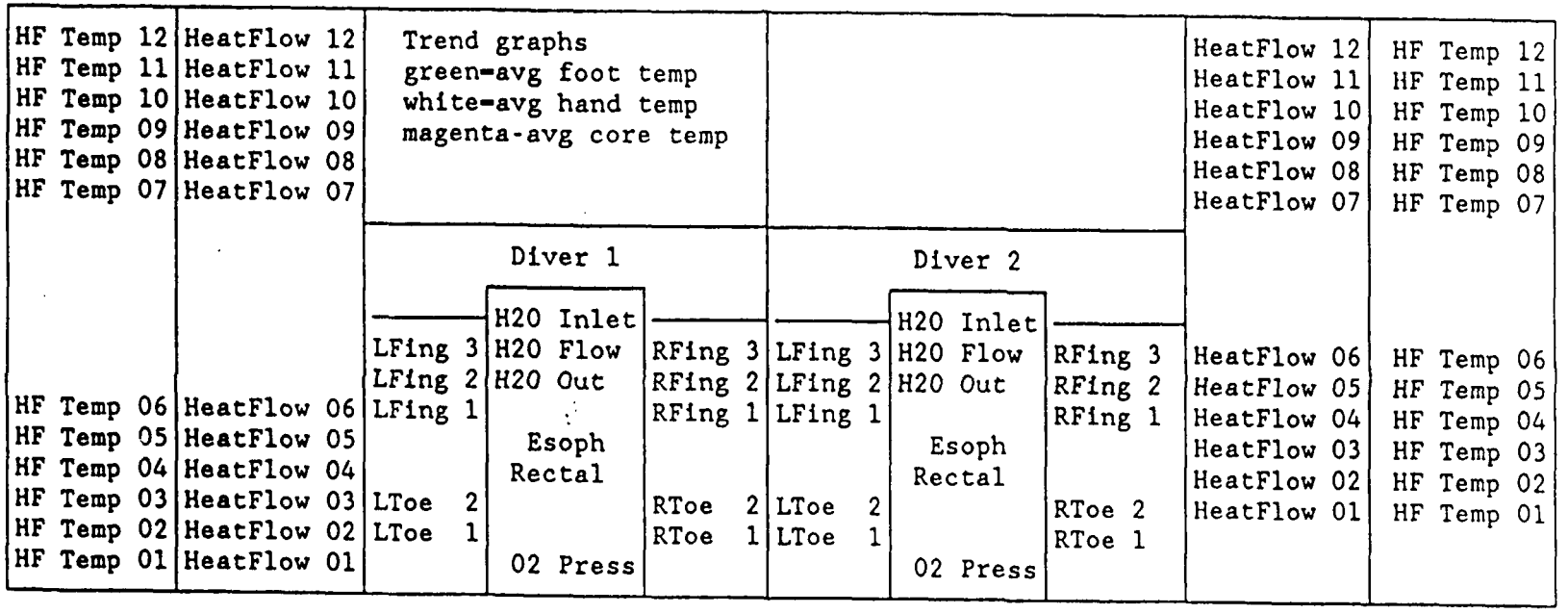


FIGURE 6 PAGE 16



Diver 1 Data

Diver 2 Data

All temperatures are in degrees Celsius
All heat flows are in watts/square meter
Oxygen bottle pressures are in PSI
Hot water flow is in GPM